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In-Service NDE of Aerospace Structures -- Emerging Technologies and Challenges at the End of the 2nd Millennium

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ABSTRACT

NDE is now a relatively mature field and, even though accurate characterization of hidden flaws may still pose a challenge, the last century has been marked with the most incredible progress. The majority of the current NDE methods were introduced around the middle of this century and the followed modifications, improvements and enhancement contributed to an unprecedented advancement in capability and reliability. Also, as an interdisciplinary field, NDE benefited from capabilities that were developed in many other fields of science and engineering. The resulting improvement touched every element of the NDE field leading to smarter instruments, which are computer-controlled, smaller, lighter and more capable. The requirements for NDE are continuing to be driven by the need for lower cost methods and instruments with greater reliability, sensitivity, user friendliness and high operation speed as well as applicability to complex materials and structures. The trend toward global market led to a growing recognition of the value of international standards covering test procedures and personnel qualification, where the documents issued by the International Standardization Organization (ISO) are becoming the leading ones. The NDE field growth is increasingly shifting into new frontiers as a result of defense budget cuts and shrinkage in government funding of research and development. Moreover, structures are being designed to require less periodic inspection using no fundamentally new material, and there is a lower need for new NDE methods to address such problems as aging aircraft. In this paper, the author made an attempt to summarize the status of the NDE field to bookmark the status at the end of this Millennium. The paper reviews emerging NDE technologies and identifies NDE challenges.

INTRODUCTION

The desire to nondestructively determine the quality and integrity of materials and structures has a very long history, where visual and tap testing have been the methods of choice for centuries. The introduction of the Magnetic Particles and Liquid Penetrant methods marked the transition to sophistication in NDE. Generally, it was well understood that any wave capable of traveling through a material is a candidate to be employed for an NDE method. The greatest progress was observed after effective data acquisition and display capabilities were developed to record and extract information about discontinuities and material properties. Around the middle of the Century, methods that rely on electromagnetic or elastic waves at various wavelengths were introduced at rapid rate [McMaster, 1963]. Fundamentally, these methods involve analysis of reflected and/or transmitted waves after interacting with the test part. The earlier methods have been Eddy Current and Radiography and were followed by Ultrasonics, Thermography and Holography. Later, during the 70's, Acoustic Emission, Magnetic Resonance Imaging (MRI) and Shearography emerged. In the absence of effective analytical tools prior to the 80's, the data interpretation depended strongly on the experience and expertise of NDE personnel. In search for new capabilities, investigators sought correlation between various material variables and physical measurements. Some of the successful results are still being applied, e.g., the estimation of thermal treatment and hardness of metallic parts using conductivity measurements. One of the main objectives of the early studies has been to determine the strength of materials and bonded joints. Soon, it was recognized that while information about the integrity and stiffness can be extracted directly from NDE measurements, strength and durability cannot be measured by NDE methods because these are statistical and not physical properties. In order to establish sound foundations for NDE using theoretical models and analytical techniques, DARPA started to fund in the early 70's research and development studies of quantitative NDE. Since that time, conferences are being held annually to foster and strengthen collaborations and provide a forum for reporting progress among the NDE scientists and engineers. Advancement in computers, electronics, and improved analytical techniques led to significant progress in quantitative NDE. Finite element models are used to investigate the effect of flaws and the structure geometrical configuration on the wave behavior and the measured response. Also, inversion techniques are being developed to determine flaw characteristics from various wave measurements. Minute flaws can be detected at high probability and repeatability with less reliance on inspector capability, thus minimizing human errors. In recent years, there has been a growing technology transition of NDE methods to new areas, including medical diagnostics, geophysics, infrastructure [Boro & Reis, 1998], remote inspection, microelectronics, micro-electro-mechanical systems (MEMS), automation, etc.

In recognition of the potential benefit of synergistic interaction with other sciences and technologies, recent ASNT conferences have been increasingly including Sessions on interdisciplinary topics. Robotics, medical diagnostics and treatment, technology transfer, miniaturization and others are now common Session topics in the semi-annual ASNT conferences and the Annual ASNT Research Symposia. The NDE research community is continuing to have the objective to improve the capability of inspection methods to reliability detect critical flaws at lower cost with minimum impact on the serviceability and life cycle of the test structure. The topic of emerging technologies and challenges is very broad, and it is very difficult to thoroughly cover is in a single paper. This manuscript is focused on the application to in-service NDE of aerospace structures.

EMERGING TECHNOLOGIES THAT ARE AFFECTING MULTIPLE NDE METHODS

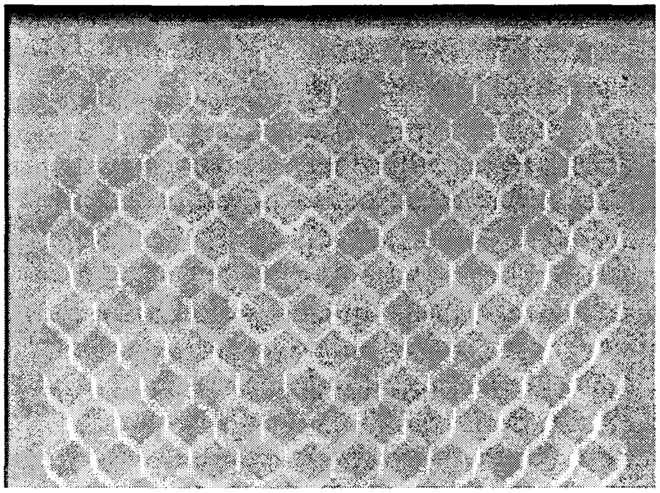
A series of advancements related to computers, electronics, material science and other interdisciplinary fields made major impact on all or many of the NDE methods. Accepting the reality that no single method can provide all the necessary NDE information, efforts are being made to integrate several methods. The complimenting capabilities offer greater detectability and the overlapping ones enhance the reliability. Data fusion techniques [Gros, 1996] are being developed to allow effective data-acquisition and processing as well as provide a sound interpretation of the test parameters in relation to the material integrity. Instruments are now commercially available that can be used to perform ultrasonic and eddy current tests using a core hardware and interchangeable transducers and modules. Also, to support such systems capability, commercial software packages are available to process data obtained from various NDE methods. Once data is acquired, the image can be analyzed and manipulated using a common set of software features. The increased processing speed and improvement in hardware is allowing real-time imaging of all the wave-base NDE methods including radiography, ultrasonics, shearography, etc. Using analytical tools, finite element analysis as well as computer hardware and software, test procedures can be developed graphically by interactive process simulation. Moreover, progress in microelectronics led to the development of miniature portable instruments that are pocket size. This section covers the technologies that affected the field of NDE in general and it will be followed by a review of specific development in the various inspection methods.

Information Highway

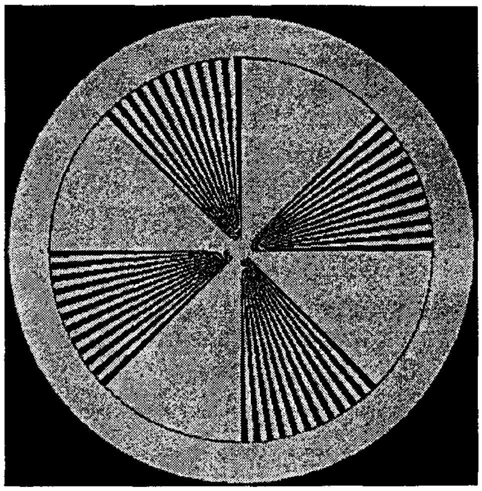
In the relatively short time since Internet became the world-wide-web as we know it, this information highway contributed greatly to the advancement of many fields including NDE [Bar-Cohen, et al, 1996]. Internet is now the information communication tool of choice for multimedia (data, files, text, programs, drawings, pictures, video and sound) at speeds, efficiency and content that cannot be matched by any other known method. NDE experts around the world rapidly recognized its power as a form of information exchange and archival. The technology is simplifying and helping to expedite the development of international standards and process specifications, as well as enabling the centralization and easing access of information achieves and databases. Formed in 1995, the global NDE Newsgroup [nde@coqui.ccf.swri.edu], which is maintained on a server at South West Research Institute, is widely used by NDE experts around the world as an electronic bulletin board. Subscribers are added electronically and they receive via e-mail inquiries, data, information and announcements of general interest. Global efforts and initiatives of individuals and companies are contributing greatly to the field. As an example, the electronic publishing forum, *NDT.net*, is a highly active and effective website that combines an electronic journal, information archive and monthly technical forums of information exchange [http://www.ndt.net/newsweb/newsweb.htm]. To take advantage of the various web capabilities the author formed the JPL's NDEAA webhub with clickable animation to aid understanding various mechanisms and with hotlinks to downloadable recent publications [http://ndeaa.jpl.nasa.gov/]. Moreover, to quickly find and access the growing number of homepages of international technical societies, the author formed the Global NDT Internet Superhub (GNIS) with clickable countries on a globe map [http://eis.jpl.nasa.gov/ndeaa/nasa-nde/gnis/gnis.htm]. The technology reached a point where "companies do not exist unless they have a homepage". To find some of the major homepage addresses, one can use the NTIAC webpage that has links to over 300 NDE site [http://www.ntiac.com/]. Through its homepages, ASNT is offering society information such as various services, conferences, and other relevant activity and announcements [http://www.asnt.org/].

Inspection Simulation

Ray tracing has been a well-established tool for investigating the travel path of waves. With the progress and increased speed of computer graphics it became feasible to use ray tracing for the development of inspection procedures using rapid interactive simulation. Simulation software can perform 3D ray tracing, and examine the wave interaction with the test structure geometry while accounting for the material that is involved. Effective tools were developed by such research institutes as the Center for NDE at Iowa State University and the Canadian National Research Council as well as commercially by UTEX (Ontario, Canada) [W. Weber, 1998]. Computer models were used to develop .user-friendly accurate and rapid simulation of such methods as radiography, ultrasonics, and eddy current. Numerous test parameters were included in the models, e.g., for X-ray simulation (see example in Figure 1) some of the parameters are X-ray source, film type, part geometry, setup distances, exposure value, material absorption, etc. The part structure can be described using 3-D CAD models, and many types of defects can be inserted anywhere into the model to form a realistic simulation of the test process. In the case of modeling ultrasonics, the reflected, transmitted and refracted waves can be used to produce simulated A-, B-, and C-scans. Further, for eddy current the real and imaginary components of the impedance-plane output as a function of the probe position can be simulated in response to crack-like defects.



a. A honeycomb sandwich.



b. A penetrameter gauge

Figure 1: Simulated radiographs using computer code and interactive graphics ((Iowa State University).

Ultrasonic test procedures can be developed using complex real-world parts (see example in Figure 2); a complete ultrasonic inspection can be simulated including the test results; difficult problems can be anticipated and diagnosed by confirming the source of the returning echoes; the sound paths in the part can be visualized; the sound field of the transducer can be evaluated to make an effective choice of the transducer; and inspectors can be easily and effectively be trained. Specifically, A-scan displays for various angles of incidence can be simulated to assist inspectors in developing ultrasonic test procedures. Longitudinal and shear mode conversions can be identified by the operator and assist in explaining the origin of echoes that appear on an A-scan display. Moreover, simulated B-scans can display how stray sound modes and part geometry might accidentally shadow flaws. If fixturing is required, the simulation software provides the necessary information for the probe angulation, spacing, delay line or water-path distances. Transducer modeling features can simulate both contact and immersion coupling using various frequencies and bandwidths as well as various focal geometries (circular, elliptical or rectangular). Tests can be viewed in both pulse echo and pitch catch and the transducer can be manipulated to follow the part surface at a fixed distance and/or inspection angle. In Figure 3, an example of the application of simulation software is shown for the inspection of an IIW calibration standard as a means of determining the resolution of the test technique. The operator can use the simulation and the results of the actual calibration to verify the efficiency of the inspection procedure. The technology significantly simplified the process of developing test procedures and the application of the simulation to process development it highly cost effective.

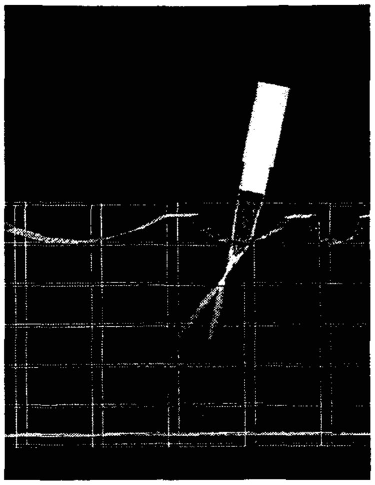


Figure 2: Simulation of the interaction of ultrasonic wave with a complex configuration using ray tracing and computer graphics [Iowa State University, http://www.cnde.iastate.edu/staff/mgarton/mgarton.html].

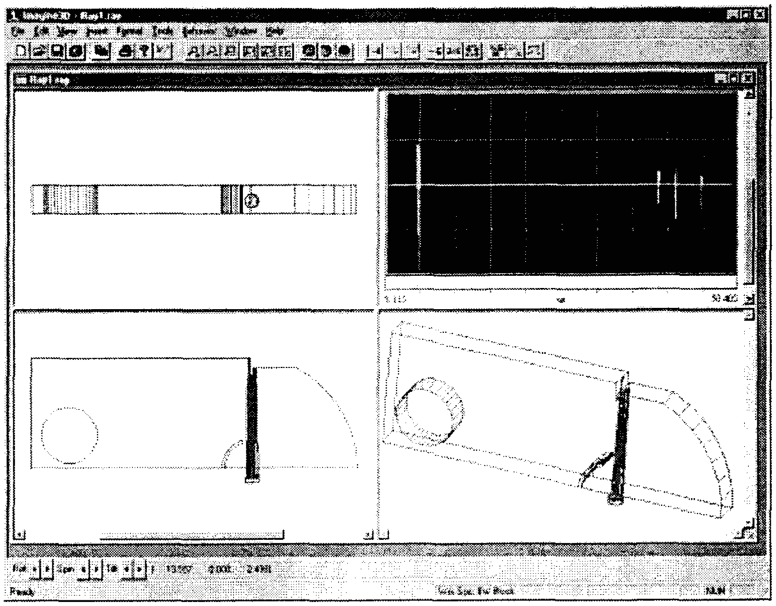


Figure 3: Inspection of an IIW block using simulation software (UTEX's Imagine3D)

Miniaturization

Progress in microelectronics enabled the miniaturization of NDE hardware and the production of portable instruments that can be carried to the field and reach difficult to access areas. Pocket size ultrasonic thickness gauges are commercially available from most of the leading manufacturers of ultrasonic instruments. The technology is leading to reduction in cost as well as in instrumentation weight and size with a great enhancement of the capability. Data acquisition cards that can be plugged into a laptop computer have been available for several years (e.g., Wesdyne International, California) and credit card size plug-in that conform to the PCMCIA type 2 standard is one of the forms in which this progress is expressed. This type of cards allow making a laptop to a small ultrasonic pulser/receiver and with appropriate software it can be operated as a complete ultrasonic data acquisition and imaging system. Such cards can be used as motion control (encoder) interfaces, high resolution A/D converters and signal processors for potable scanners. The systems are battery operated and increasingly they are employing wireless communication capabilities.

The technology of miniaturization has impacted also the size of sensors and their support electronics. For over ten years, the trucking industry has been using tires with imbedded sensors that wirelessly communicate every several minutes the individual tires' identity and pressure. Using effective power management, these sensors can operate for periods of more than 8 years without needing to change battery. This technology is intended to help truck drivers to avoid tragic and costly accidents that can result from a flat tire. Another area of automotive that benefited from the miniaturization technology is impact sensing and activation mechanism of airbags. Further, insects such as bees are commonly tracked with the aid of miniature transmitters that are installed as backpacks. Such capabilities can be transitioned to the field of acoustic emission and other NDE if miniature wireless stick-on sensors are used. The size of electronics has become so small that insects can be instrumented to perform tasks that used to be view as science fiction. Example is shown in Figure 4, where a spider at the University of Tokyo, Japan, was instrumented as a locomotive to carry a backpack of wireless electronics. Development in actuation technology is expected to lead to insect-like robots that can be launched into hidden areas like aircraft engine and perform inspection and maintenance tasks. Beside miniaturization of conventional actuators, such as motors, electroactive polymers are being developed to offer the closest emulation of biological muscles. In Figure 5 an example is shown of a bending type electroactive polymer operating as a dust remover similar to an automotive windshield wiper [Bar-Cohen, et al, 1998].

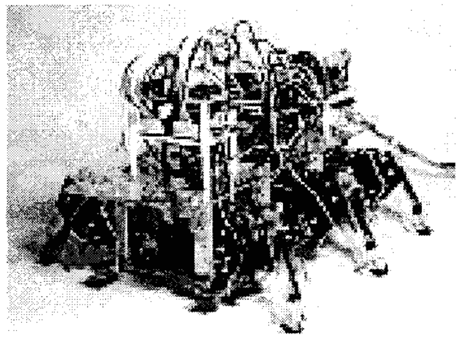


Figure 4: An instrumented spider at the University of Tokyo illustrates the potential to NDE in terms of mobile sensors [http://www.leopard.t.u-tokyo.ac.jp/].

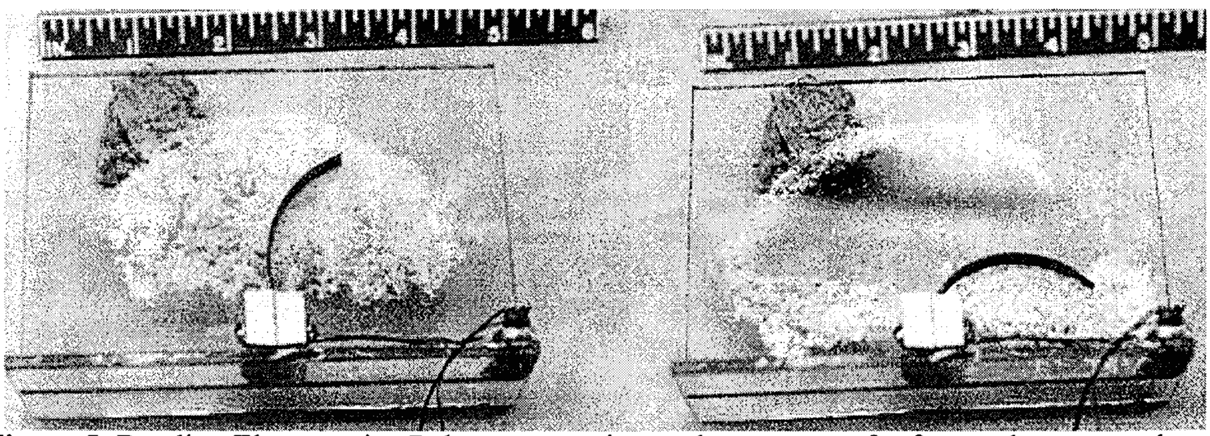


Figure 5: Bending Electroactive Polymer operating as dust remover for future planetary tasks. Potentially, these materials will operate similar to biological muscles to drive insect-like robots.

Rapid field inspection

Performing NDE using such methods as ultrasonics and eddy current, which require a probe to obtain data and scanning to cover a large area, is time consuming and involved difficulties when applied in field conditions. Rapid inspection of large structures is an ongoing challenge to the NDE community. The need for such a capability grew significantly in recent years as a result of the increase in the numbers of aircraft with composite primary structures and of aging aircraft still in service. Generally, metallic structures are susceptible to corrosion and fatigue cracking whereas composites are sensitive to impact damage that can appear anywhere on the structure. Using manual scanning, field inspection is labor intensive, time consuming and susceptible to human error, whereas removal of parts from an aircraft for a lab test is costly and may not be practical. Effective field inspection requires a portable, user friendly system that can rapidly scan large areas of complex structures. In recent years, various portable inspection systems have emerged including scanners that are placed at selected locations and sequentially repositioned to fully cover the desired areas [Bar-Cohen, 1999a]. An example of such scanner is shown in Figure 6, where vacuum suction cups are used to secure the scanner-bridge to the test structure. The development of such scanners requires multidisciplinary expertise including NDE, telerobotics, neural networks, automated control, imbedded computing and materials science. The capability of the developed systems followed the technology evolution and the overall trend is towards full automation with a desire to have a completely autonomous inspection.

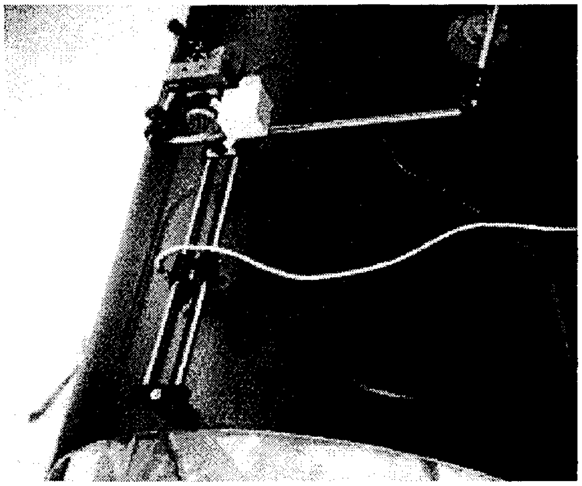


Figure 6: A scanner is secured to a test structure using suction cups (QMI, Costa Mesa, CA).

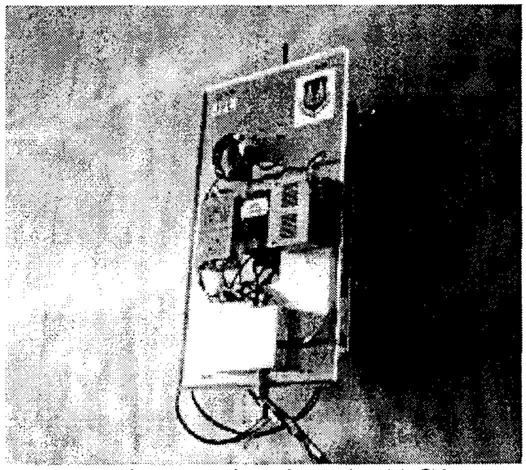


Figure 7: The JPL developed MACS crawling on the C-5 aircraft (patent pending).

Increasingly, crawling devices are reported as a solution to the need for rapid inspection and the use of suction cups has become a leading form of controlled adherence. Several successful mobile portable scanners have emerged in the last several years, including the Automated Non Destructive Inspector (ANDI) and the Autocrawler [Bahr, 1992, and Siegel, 1998]. Recently, JPL developed the Multifunction Automated Crawling System (MACS) offering an open architecture robotic platform for NDE boards and sensors [Bar-Cohen, 1999b]. MACS is a small, highly dexterous crawler designed to perform complex scanning tasks. It uses suction cups for controlled attachment and flexural ultrasonic traveling wave motors for mobility. MACS (shown in Figure 7) was designed to inspect large structures particularly in field and depot conditions and it established the foundations for the development of a "walking" computer platform with standard plug-in NDE boards. This concept offers a larger pool of companies and individuals the opportunity to become potential producers of NDE instruments. Thus, a significant cost reduction can be materialized with a rapid transition of novel concepts to practical use. The potential formation of large pool of users and developers would lead to rapidly improving, affordable and tailorable systems with a potential success similar to the personal computers.

Remote monitoring is one of the avenues of future development where centrally located experts can be responsible for the inspection and they will be equipped with know-how, database, analytical tools, CAD drawing, and accept/reject criteria. These experts will need to deal only with questionable information where the redundant non-defective areas will be screened by the crawler system. Controlling the crawler remotely via Internet using password will allow authorized users to simultaneously viewing and operating it. Inspection needs can be addressed rapidly, particularly in cases of crisis where it is necessary to examine a full flight of a particular aircraft model all over the world. A combination of visual, tap testing, eddy current, and ultrasonics are expected to be the leading NDE capabilities for integration into MACS. The evaluation of flaws using multiple NDE methods requires data fusion [Gros, 1996] and neural network data interpretation. Programming the travel on complex structures can employ telerobotic capabilities similar to the one developed for the exploration of Mars, including the rover of the Mars Pathfinder mission. MACS is currently using an umbilical cord for power, control, and communication as well as pressure tubing for ejection and activation of the vacuum suction cups. Further enhancement will be the development of an autonomous crawler for operation during aircraft idle time to reduce the need to ground aircraft for inspection. This will require a miniature on-board vacuum pump, power and computing capabilities. To protect aircraft elements that rise above the surface from accidental damage, a vision system and collision avoidance software need to be used. Employing local Global Positioning Systems (GPS) can provide absolute coordinates without the need for complex, costly and heavy encoders. The information regarding the location of the crawler on the aircraft in relation to the detailed drawings can help assessing flaws criticality.

Testbed for Validation of New NDE Techniques

The need for a testbed to demonstrate new NDE techniques and instruments hampered their transition to a practical use. In August 1991, an FAA center for NDE was formed at Albuquerque, NM, to offer a validation testbed consisting of aging aircraft with known flaws. This Sandia National Laboratories' Airworthiness Assurance Nondestructive Inspection Validation Center (AANC) was facilitated with a series of aging civilian aircraft and a library of structural parts with documented flaws [http://www.sandia.gov/aanc/pubs.htm, Smith & Shurtleff, 1997 and Shurtleff, et al, 1997]. The center arose out of the Aviation Safety Act of 1988, passed by Congress after the midair structural failure of the Aloha Airlines Boeing 737. Sandia's role has since been expanded to other areas covering aircraft overall safety system design such as fire protection, information system management, and accident investigation support. A view of one of the aircraft that is available at the AANC facility is shown in Figure 8.

Figure 8: An aging aircraft with well documented flaws at AANC.

EMERGING NDE TECHNIQUES

Beside the improvement of NDE overall, the various NDE methods have seen an emergence of new techniques with superb capabilities and speed. The specific methods that will be covered herein are visual, eddy current, radiography, ultrasonics, radiography, shearography and thermography.

VISUAL

Visual inspection is continuing to be the leading NDE method and it represents the highest percentage of the inspection procedures that is applied to aircraft in service. To enhance the inspection capability, new tools were developed including improved illumination techniques, miniature video and dexterous small-diameter boroscopes. In recent years, two visual inspection techniques have emerged that worth noting and they are the D-Sight and the Edge of Light (EOL). While D-Sight already found its way to practical use, the EOL technique is relatively new and it is still in development stages.

Dual-Pass Light Reflection (D-Sight™)

Surface and near-surface flaws, such as corrosion in metals and impact damage in composites, are causing a local surface deformation. The visual inspection technique called D-Sight (Diffracto Limited) enhances the appearance of this deformation and increases its visibility [Forsyth, et al, 1998]. A D-Sight inspection system consists of a CCD camera, a white light source mounted slightly above the camera lens, and a retro-reflective screen [http://www.diffracto.com/products/dsight/dsight.htm]. In Figure 9, a schematic view is showing the principle operation of D-sight and on the right an example of test result for cold worked holes can be seen. The system's screen is made of a reflective micro-bead layer and is the most important element of the D-Sight system. While the screen returns most of the light in the same direction of the incidence, a slight amount of light is dispersed. When a surface is illuminated by a light source, local surface curvatures are focusing or dispersing the light onto the retro-reflective screen. A light pattern is formed on the screen and is reflected back to the source with a slight dispersion. This path of the light is backlighting the part surface and enhances the scattering effect of surface deformations. By viewing the surface slightly off-axis from the light source a unique pattern appears near local surface deformations. This pattern consists of bright and dark gray scale variations, where higher curvatures appear more intense due to the effect of focusing and diffusing the light. To obtain a sufficient level of diffused light the surface must be reflective, otherwise a thin layer of liquid needs to cover the surface to increase its reflectivity.

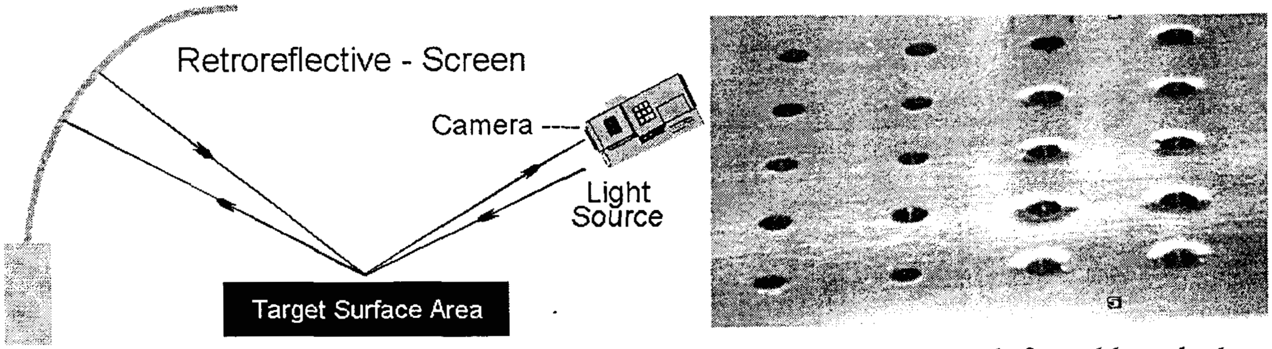


Figure 9: D-Sight principle of operation (left) and an example of the test result for cold worked holes.

Edge Of Light™ (EOL)
Another method of enhancing the surface deformation that is caused by flaws is the Edge of Light™ (EOL), which was developed by the National Research Council Canada [Forsyth, et al, 1998]. It employs elements commonly used in optical scanners and it uses the scattered light from surface deformation and variations in the surface slope to produce an image that consists of light intensity variations. The technique is relatively quick, with scanning speeds in the order of 2 to 20-linear cm/sec with line scan widths of 10-cm or more. EOL inspection results are easily interpreted, as they closely resemble the actual subject. The technique has been demonstrated to be effective in detecting corrosion in surfaces and joints, as well as flaws in gas turbine components and turbine disks. For some applications, EOL was shown to have superior detection capability over liquid penetrant, magnetic particle, ultrasonic inspections, or optical microscopy. In Figure 10, a comparison is shown between an unaided view and EOL image of corrosion pillowing in a lap splice joint of a Boeing 727.

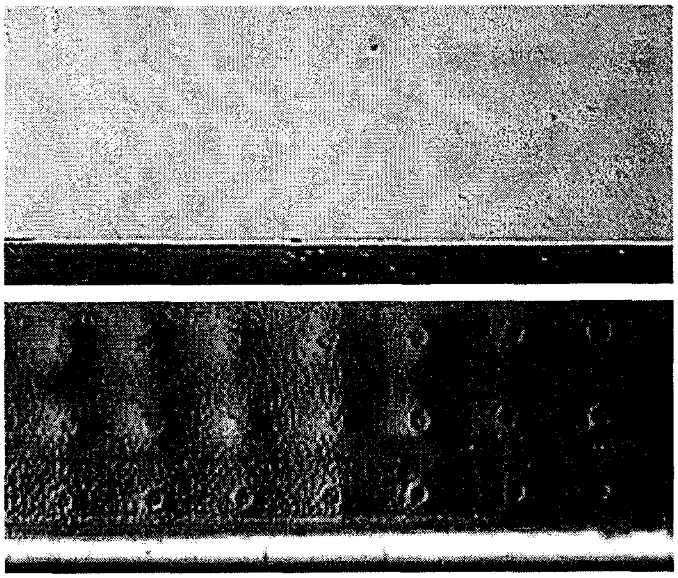


Figure 10: ***Top*** - Lap splice joint from a Boeing 727, as seen by the unaided eye. ***Bottom*** - EOL image of the same joint clearly showing corrosion pillowing

EDDY CURRENT

For over three decades, eddy current has been one of the leading in-service inspection methods for crack detection around and inside fastener holes. Significant improvement has been made to enhance the method capability, reliability and user friendliness. The modeling of the effect of flaws contributed significantly to the understanding of the key parameters as well as the reduction in the effect of noise and liftoff. Improved probes and instrumentation were developed and the effective use of low frequencies enabled inspection of metallic layered structures for detection of flaws in the second and third layer. The Magneto-Optics Imager (MOI) has been one of the eddy current technique spin-offs and it is being practically implemented by the aircraft industry. Another eddy current technique that has emerged in recent years is the pulse eddy current. The early phases of the development of this technique were made at Iowa State University and South West Research Institute and currently it is being transitioned to a practical hardware at the Canadian National Research Council. Further, To detect cracks in thick or multilayered metallic structures, the method called SQUID was developed.

Magneto-Optics Imager (MOI)

In order to simplify the detection of flaws, the Magneto-Optics Imager (MOI) was developed as a means of visualizing the eddy current response [Thome, 1997]. The Magneto-Optic Imager (MOI) combines planar eddy current and magneto optic imaging and it is applicable to inspection of metallic structures for surface and subsurface flaws. MOI is able to image through paint and other surface coverings in real time and to project the results on a heads up display and/or a monitor. MOI is employed in a hand-held (see Figure 11) portable instrument that requires minimal training and its capability greatly increases the speed and reliability of inspection. This method is currently being used extensively for aircraft inspection by airlines, maintenance facilities and the military.

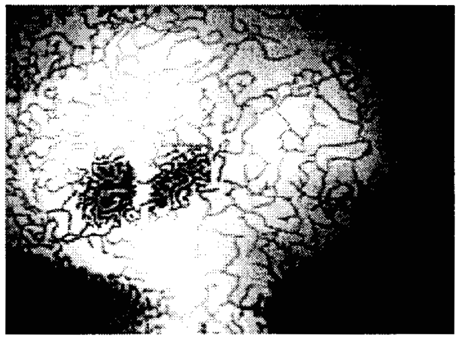


Figure 11: A photographic view of an MOI inspection (left) and an image of 5-mm notch in the third layer of a lap-joint (right) using 3KHz multidirectional excitation (PRI Instrumentation)

Pulsed Eddy Current (PEC)

Conventional eddy current techniques use single frequency sinusoidal excitation and measure flaw responses as impedance or voltage changes on an impedance plane display. To detect flaws, inspectors interpret the magnitude and phase changes, but the method is sensitive to variety of parameters that are hampering the characterisation of flaws. Multiple frequency measurements can be combined to more accurately assess the integrity of a structure by reducing signal anomalies that may otherwise mask the flaws. Initial development led to the use of dual frequency eddy-current where frequency-mixing functions allowed the quick application of the technique. This approach has been shown to be useful in reducing the effects of plate separation variations when inspecting for second layer corrosion in lap splices [Thompson, 1993]. The dual frequency method offers advantageous when performing large area inspections by means of eddy current C-scans of specimens with corrosion under fasteners [Lepine, 1997]. Unfortunately, conventional multiple frequency methods can provide limited quantitative data and are difficult to use for flaw visualisation in an intuitive manner.

Swept frequency measurements using impedance analysers perform well in quantitative corrosion characterisation studies, especially when they are interpreted in conjunction with theoretical models [Mitra, et al, 1993]. However, the application of these techniques is too laborious. In contrast to the conventional eddy current method, pulsed eddy current (PEC) excites the probe's driving coil with a repetitive broadband pulse, such as a square wave. The resulting transient current through the coil induces transient eddy currents in the test piece, associated with highly attenuated magnetic pulses propagating through the material. At each probe location, a series of voltage-time data pairs are produced as the induced field decays, analogous to ultrasonic inspection data. Since a broad frequency spectrum is produced in one pulse, the reflected signal contains flaw depth information. Physically, the pulse is broadened and delayed as it travels deeper into the highly dispersive material. Therefore, flaws or other anomalies close to the surface will affect the eddy current response earlier in time than deep flaws. Similar to ultrasonic methods, the modes of presentation of PEC data can include A-, B- and C-scans [Bieber, et al, 1998]. Interpretation, therefore, may be considered more intuitive than conventional eddy current data. The excitation pulse, signal gain and sensor configurations can be modified to suit particular applications. Examples of C-scan results of testing two plat layers with various degrees of thickness loss on the top of the second layer are shown in Figure 12.

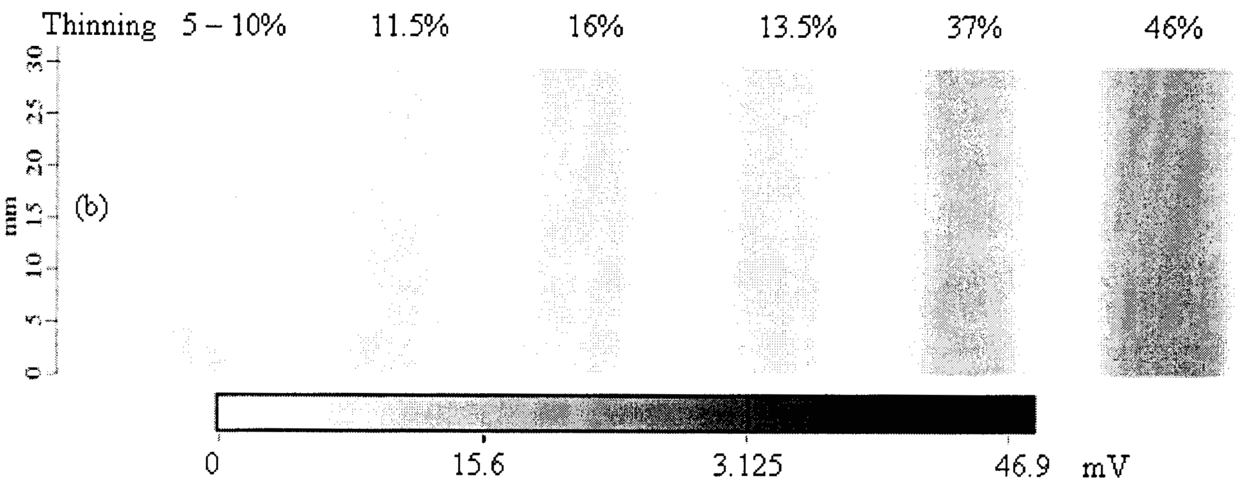


Figure 12: PEC amplitude c-scan of 2-layer plate specimen with metal loss located at the top of the second layer.

Superconducting Quantum Interference Device (SQUID)

SQUID is a magnetic field sensor for eddy current measurements that are highly sensitive even at low frequencies. SQUIDs in general have a very high magnetic field sensitivity, which is nearly independent of frequency. This offers an advantage for magnetic field sensor for applications where a low excitation frequency especially for large depth of penetration. The technique requires cooling to cryogenic levels and it has been demonstrated to be highly effective in flaw detection. Recent research in SQUID based NDE systems [e.g., Kreutzbruck, 1998] has proven their superiority over conventional systems when searching for cracks in depth of 10 mm or more [Ma and Wikswo, 1994]. Further, it was shown to have an improved signal to noise ratio of up to 3 orders of magnitude for cracks deeper than 13mm. Additionally, the high bandwidth available with certain SQUID systems make measurements over a wide frequency range possible without having to change the sensor. The high dynamic range (the ratio between the highest field change which can be measured before the system goes into saturation and the lowest detectable field) allows one to detect small field changes in the presence of large background fields, produced e.g. by edge effects or inhomogeneities in conductivity. The method is effective mostly in low frequency applications for the detection of deep lying defects, in multilayer structures, rivet plates and aircraft wheels. One concern that need to be take into account is that for deep structures the eddy currents spread over a larger area and the spatial resolution might be too low for practical purposes. The large dynamic range of SQUID allows shorter integration time and therefore faster scanning is possible. Figure 13 shows the eddy current field distribution above a sample with 40-mm long and 0.6-mm high crack tested through a 13-mm thick aluminium plate. Depending on the variation of the conductivity of the covering plate, a substantial background occurs, which limits the reliable detection of deep lying and small cracks.

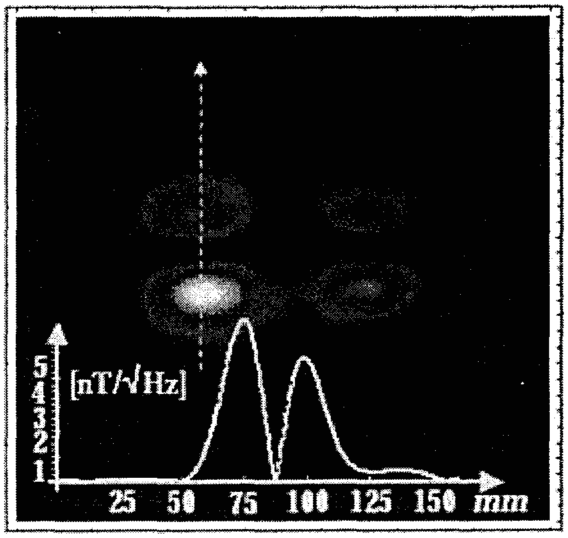


Figure 13: The field distribution above a sample with 40 mm long and 0.6 mm high crack covered by a 13 mm thickness aluminium plate. [Kreutzbruck, 1998]

RADIOGRAPHY

The capability of radiography to provide an image that is relatively easy to interpret made it an attractive NDE method for both industrial and medical applications. The health hazard associated with the exposure to this ionizing radiation and the use of films to record the images constrained the application of radiography. The development of real time imaging techniques for radiographic visualization helped overcoming the time consuming process that was involved with film recording. Moreover, computer processing of digitized images enabled the enhancement of the images as well as the quantification of the inspection criteria. Several radiographic techniques that deserve attention include the CT scan, Reverse Geometry X-ray and Microfocus X-ray microscopy.

Compute Tomography Scan

Computer processing of the distribution of X-ray transmission coefficient in a structure using a series of viewing angles is used to produce computed tomography (CT) scan [Kak and Slaney, 1988]. This radiographic technique has been widely in use as an important medical tool for over three decades. At the early 80's the technique was transferred to industrial use by researchers at the Air Force Materials Laboratory. The method is highly effective in testing composite structures and it provides a quantitative information about the distribution of the material density. Images can be produced and manipulated in a real-time format and allow recognition, localization and classification of material defects (e.g. pores, blowholes, foreign bodies). The inspection can be done automatically in arbitrary test samples (e.g. in metal, ceramic, glass or synthetic material castings). Three-dimensional position and extension of a defect can be determined by evaluating pairs of stereoscopic transmission images [Chen, et al, 1990]. Depending on the object geometry, the acquisition of stereoscopic images can alternatively be done by translation or rotation of the sample. The defect extension in direction of transmission is calculated by using the absorption law adapted for polychromatic radiation. An example of a graphite/epoxy sample is shown in Figure 14.

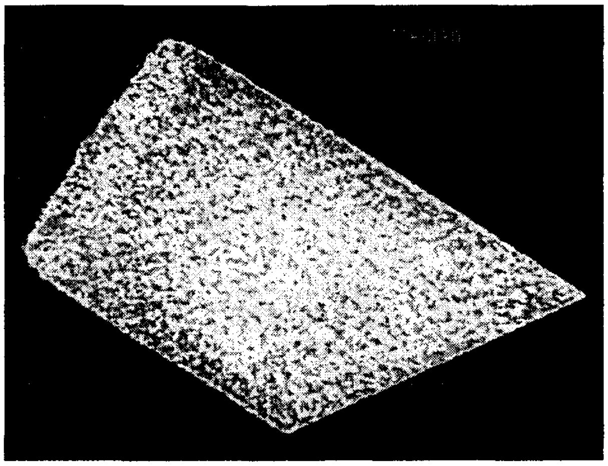


Figure 14: CT image of the density distribution in a reference graphite/epoxy sample.

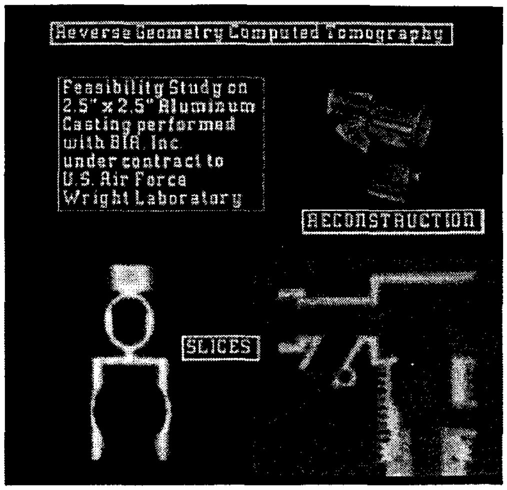


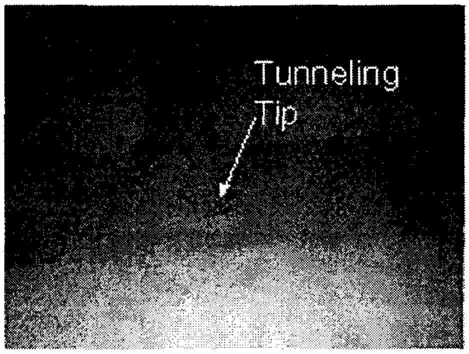
Figure 15: Reverse Geometry test of an aluminum casting showing various slices (Digiray).

Reverse Geometry X-Ray (RGX) Imaging

In contrast to conventional radiography, RGX reverses the relative sizes of source and detector as well as the location of the object [Dolan, et al, 1993]. The object is placed adjacent to the large, computer controlled raster-scanning source at a distance from the point detector. This arrangement allows scattered radiation to bypass the detector, thereby increasing the contrast sensitivity (signal-to-noise ratio). The method has been demonstrated to detect such flaws as corrosion, impact damage, and water entrapment in aluminum and composites. In the case of corrosion on aircraft, it was possible to detect the loss of material down to as little as 1.0%, even when the material loss is disguised by the presence of corrosion products. An example of a Reverse Geometry image of an aluminum casting is shown in Figure 15, where various slices can be viewed. The distance between object and detector can be easily increased to reduce parallax effects and increase throughput for large area honeycomb and/or thick honeycomb inspection.

Microfocus X-ray Microscopy

Using a small source to provide a great magnification of the inspected object, Microfocus X-ray Microscopy operates similarly to conventional radiographic techniques [Olivas, et al, 1997]. Conventional radiographic techniques generate X-rays from a thick target, typically tungsten, oriented at 30^{o} or 45^{o} angles to the electron beam source. X-ray images are produced with limited magnification. Through the use of a thin film target oriented normal to the electron beam source, samples are positioned opposite to the beryllium window thereby minimizing working distance and maximizing magnification. The microfocused beam (~3 μm) further enhances resolution by increasing sharpness of the image as compared to the one obtained using larger focal spot sizes. Geometric magnification for typical fine-focus applications are ranging from ~3X to 1000X with capabilities of extending beyond 2000X. For conventional transmission microfocus X-ray, the tube voltage ranges from 10 - 225kV with focal dimensions from 3 to 200 µm. By manipulating the sample and viewing a real-time image, defects normally obscured in conventional 2-D background noise can be readily imaged. The technique is widely used for NDE of microelectronics and aerospace applications for parts with miniature internal components. An example of images obtained using Microfocus X-ray from two different viewing angles are shown in Figure 16, where a hydrophone with a microns size tunneling tip was examined.



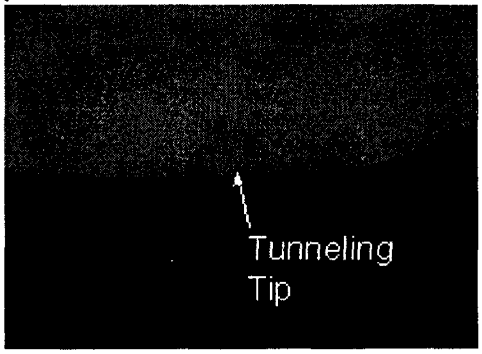


Figure 16: Microfocus X-ray image of a hydrophone tunneling tip as viewed from isometric (left) and profile (right) views.

ULTRASONICS

Ultrasonics is one of the most versatile and informative NDE methods. The various modes that these waves can support allow the extractions of detailed information about flaws as well as determining various material properties. Techniques were developed employing the various wave modes as well as scattering and mode-conversion that are associate with the wave interaction. Such techniques include the Acousto-Ultrasonics, which is practically used for flaw screening, and the ultrasonic angular insonification to induce the polar backscattering and leaky Lamb waves. Also, to perform rapid inspection portable scanners were developed, as mentioned earlier. To simplify the imaging process without the use of mechanical scanning array transducers and CCD technology has been used to form the ultrasonic equivalence of the video cameras. The difficulties associated with the need for liquid couplant, which affected mostly field applications, led to the development of various fixtures including water filled boots and wheels, bubblers and squirters. Recently, a dripless bubbler was developed at Iowa State University where water is recycled using a vacuum pump [Patton and Hsu, 1998]. Even though the bubbler adds significant mass to the probe mount, it maintains most of the water and it was demonstrated as an effective method of performing the equivalent of immersion in field conditions. Alternative dry coupling methods were also developed including the use of air-coupled piezoelectric transducers, Electro-Magnetic Transducers (EMAT) and Laser Ultrasonics [Green, 1997].

Dry Coupling Techniques

The inability to transmit and receive ultrasonic waves through air or gas was a limiting factor in developing rapid field inspection as well as testing materials that are porous or water sensitive.

Most ultrasonic NDE applications operate at frequencies in the range of 1- 10 MHz, where traveling through air is highly attenuative. The acoustic impedance of air differs significantly from the one for the piezoelectric transmitter and test part causing reflections. Therefore, only a very small fraction of the energy is transmitted through the part and the transducer interfaces.

Air-Coupled transducers

One solution to overcoming this air-coupling problem without using additional transition media can be the induction of sufficiently high sound level and using high-gain, low-noise amplification [Grandia & Fortunko, 1995, and Wykes, 1995]. To enhance the transmitted energy, the transducer needs to be used with no backing layers and thus taking advantage of the high mechanical-quality factor Q of piezoelectric disks. Also, to improve the generation and reception efficiencies of the transducer, its front protection layer is made of a thin porous material having low specific impedance. The transducer needs to be driven by tone-bursts with a center frequency that exactly matches the thickness-mode resonance. In addition, using focused transducers one can further increase the sound pressure and sensitivity. Such modifications of the transducers and hardware allowed the operation of air-coupled ultrasonic C-scans at frequencies at the Megahertz range. While it is still limited to materials with relatively low acoustic impedance, such as composites, it is already being used extensively at various industrial applications where water can not be used as a coupling medium. In Figure 17, an example of a C-scan is shown where a solar honeycomb panel with a 5x5-cm stiffener insert was tested using a 400 KHz air-coupled through-transmission. The bonded honeycomb core, the area of the insert and the missing core can be seen easily.

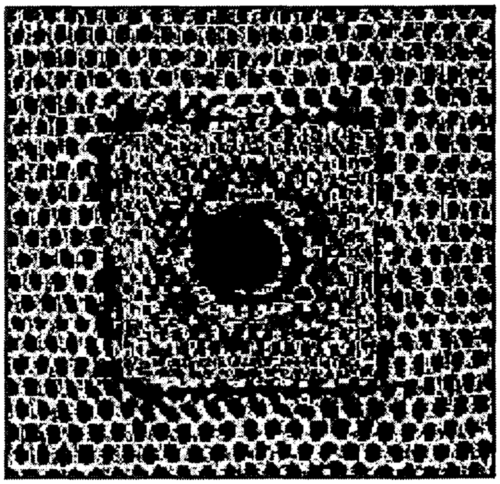


Figure 17: A 400 KHz air-coupled through-transmission C-scan of solar honeycomb panel with a 5x5-cm stiffener insert [Grandia & Fortunko, 1995].

Electromagnetic acoustic transducer (EMAT)

EMAT is a type of transducer that uses eddy current to generate and receive acoustic signals and it offers the capability to perform dry coupling [Oursler & Wagner, 1995]. The method allows the induction of specific ultrasonic modes including normal beam and angle-beam shear wave, Shear Horizontal (SH) plate wave, Rayleigh wave and Lamb wave [Hübschen, 1998 and Hutchins, et al, 1987]. The ability to induce horizontally polarized shear waves has a great significance for the inspection of austenitic welds. Another advantage of this type transducer is their ability to operate at high temperatures. However, the main disadvantage of EMAT arises from its relatively low transmitted ultrasonic energy constraining the transducer dynamic range by electronic noise. As a result, such transducers are limited to the lower frequency range. Another effect that is associate with the low transmitted energy is the critical dependence of the induced energy on the probe proximity to the test object. For practical applications, this distance is commonly maintained below 1-mm.

Laser induced ultrasound

Laser ultrasonics is one of the effective methods of inducing and receiving ultrasonic waves without the need for a couplant. The received signals are evaluated very similar to the pulse-echo technique and parts can easily be scanned from a distance of about 3-4 meters. The method induces short pulses in the range of 10-μsec causing a rapid heating and expansion of the surface forming elastic pulses. The reflected signals are examined by an interferometric setup and such systems were developed by several universities including the Center for NDE at John Hopkins University as well as the Canadian National Research Council [e.g., Scruby &. Drain, 1990 and Monchalin, et al, 1998]. Also, a commercial system was developed by UltraOptec (Québec, Canada), who delivered one of its products to the Air Force maintenance facility at McClellan Air Force Base for inspection of composite and bonded structures [Fiedler, et al, 1997]. The method is effective for inspection of structures with complex geometry allowing examination of surfaces with a slop of up to about $\pm 45^{o}$. This allows mapping defects in parts that are contoured and presenting the results in 3-D (see Figure 18) and there is no critical orientations requirement for the incident beam. The limiting factor in the scanning speed is the inability to induce pulses at high rate, where an average of 100 pulses/sec is commonly used. Overall, the cost and the sensitivity of the laser ultrasonic technique are limiting the wide usage of laser ultrasonics. New techniques are continuously being introduced in an effort to reduce the cost of the hardware. However, the sensitivity is fundamentally limited to about 45dB because there is a lower bound for the sensitivity to detection of a single phonon, whereas the upper limit is set by the desire to avoid thermal damage to the surface of the test structure. The commercially available systems offer user friendly imaging software which displays A-scans, B-scans and C-scans as well as 3-D ultrasonic images that can be easily manipulated for various angles of view.

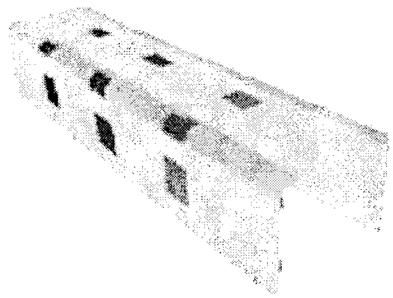


Figure 18: A 3-D C-scan image of a curved part with flaws at various depth (identified in colors) using laser ultrasonic time-of-flight. [Monchalin, et al, 1998]

NDE of Composites using Oblique Insonification

Composite materials are now making a significant percentage of aircraft and spacecraft flaw critical structures. These materials susceptibility to flaws during production and assembly as well as the cost associated with their inspection are issues of concern to the NDE community. Moreover, these materials are reaching service duration for which flaws due to aging are requiring a greater attention. Standard NDE methods, which were developed to inspect metallic structures, were adapted by the industry for inspection of composites partially accounting for the multi-layered anisotropic nature of these materials. The adapted NDE methods provide limited and mostly qualitative information about the material properties and defects. The author discovery of the ultrasonic Polar Back-Scattering (PBS) [Bar-Cohen & Crane, 1982] and the leaky Lamb wave (LLW) [Bar-Cohen & Chimenti, 1994] phenomena (1979 and 1982, respectively) in composites added a powerful arsenal of quantitative NDE methods. These phenomena are based on obliquely insonified ultrasonic waves and the numerous analytical and experimental studies followed the discovery of these phenomena are helping to pave the way for the application of these techniques. Using PBS, the fiber orientations can be determined and porosity clusters as well as fatigue cracks can be mapped. Further, using inversion of LLW data, the elastic properties of composite panels can be determined, flaws can be characterized uniquely, and the quality of adhesive bonded-joints can be determined [Bar-Cohen, et al, 1993 and 1999 and Bar-Cohen, 1990]. The LLW data is acquired in the form of dispersion curves that show the phase velocity as a function of the frequency along various polar angles with the fibers. To harness the capabilities that are offered by LLW and PBS, a computer-controlled scanner was developed jointly with QMI (Costa Mesa, CA) as a C-scan attachment. In Figure 19, the scanner is shown to consist of an arch. The arch plane represents the polar angle of the acquired dispersion curve, whereas the angle of incidence of the two transducers is controlled and guided by the arch. The height of the transducer pair as well as the polar and pitch-catch angles are all controlled at high precision. Recent enhancement of the data acquisition is enabling rapid acquisition of dispersion curves at such a speed that a curve for 20 angles of incidence is obtained in less than a minute. Rapid acquisition of dispersion curves is very important for the practical implementation of quantitative mapping of laminates material properties. Using the new capability, LLW modes with a very low amplitude are now possible to record as shown in Figure 20.

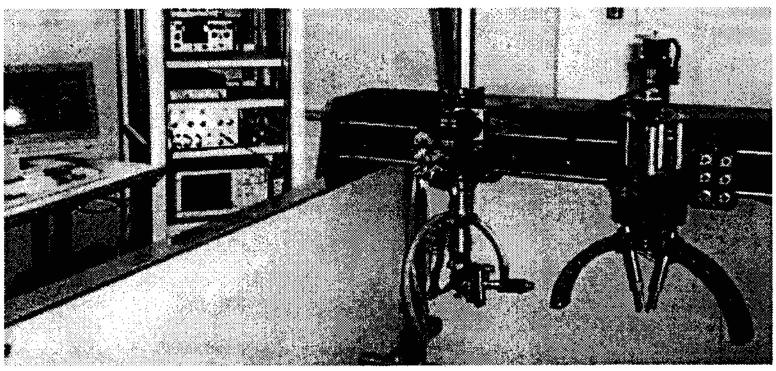


Figure 19: The LLW scanner attachment on the JPL's C-scan system.

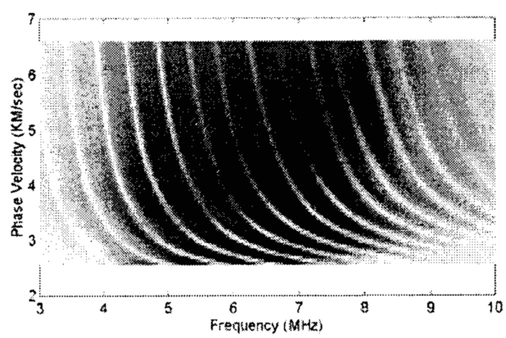


Figure 20: A new method of acquiring dispersion data, developed at JPL, allows recording very low amplitude modes..

Portable Real-Time Imager Using CCD

Ultrasonic imaging using a portable real time system that employs a two-dimensional sensing array has been shown to be an effective means of field inspection [Lasser & Harrison, 1997]. An ultrasonic camera displays the images at TV frame rates and this capability contrasts the conventional C-scan, which generates the image by scanning the test area point-by-point. This real-time imager offers a portable, practical tool for rapid visualization of flaws using an integrated circuit, which converts ultrasound data into a standard TV output, enabling ultrasound imaging of an area in real time. The system operates as a pulse-echo tester (as shown schematically in Figure 21) and it is designed to display different depth views by examining various ranges of time-of-flight. The inspector applies an ultrasonic couplant over the desired test area. Then, the probe assembly is placed against the target using the pistol grip and the ultrasonic wave insonifies the target area upon squeezing a trigger. The ultrasonic pulse-echo image of the test structure appears on a small LCD screen mounted on the back of the probe. Controls are located on the handle facing the user and real-time adjustments can be made to select the desired contrast, gain, ultrasound power, pulse-echo power, etc. An example of corrosion detected in an aluminum plate is shown in Figure 22.

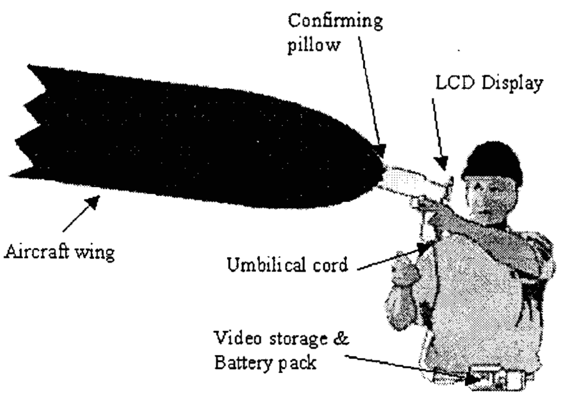


Figure 21: A schematic view of the ultrasonic video viewing system operated in field conditions (Imperium).

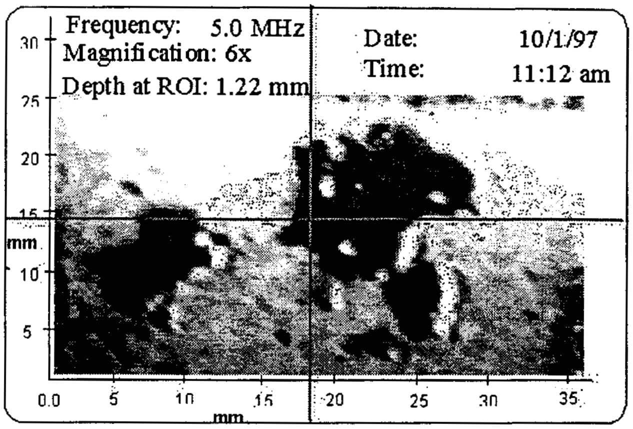
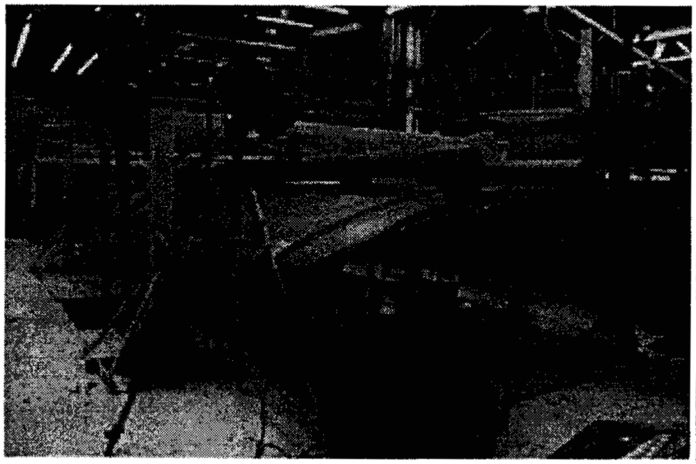


Figure 22: Pulse-echo image of corroded aluminum plate. The depth data represents the information at the crosshair cursor location.

SHEAROGRAPHY

The ability of holography to produce flaw indications superpositioned onto a 3-D image of parts has been a desirable feature, which was well documented since the 60's. The process involves double exposure of the structure at two different stressing levels. Unfortunately, the method has been very sensitive to vibrations or displacement of the setup and therefore was not practical for field use. The introduction of the shearography as a technique of forming double exposure without concern to the system mechanical stability made it highly attractive. A digital interferometry system is used to detect areas of stress concentration caused by anomalies in the material [Maji, 1997 and Walter, 1991]. The technique senses out-of-plane surface displacements in response to an applied load. Data is presented in the form of a fringe pattern produced by comparing two states of the test sample, one before and the other after a load is applied. Electronic shearography incorporates a CCD camera and frame grabber for image acquisition at video frame rates. Fringe patterns are produced by real time digital subtraction of the deformed object image from the reference object image. Shearography also uses a `common-path' optical arrangement, which provides reasonable immunity to environmental disturbances such as room vibrations and thermal air currents. As a result, shearography can be implemented without the need for sophisticated vibration isolation that is required for conventional holography. The capability of Shearography to inspect a large area in real time has significant advantages for many industrial applications and is being practically used for inspection of composite structures and pressure vessels. Northrop Grumman Corp. has been using shearography on the B-2 program since 1988. The method is being applied for inspection of bonded composites and metallic assemblies for which experience has shown inspection time reduction of about 75% compared to other NDE methods. Further, there are many cases where this method was found to be the only one capable of detecting the specific flaws.

To address the requirement to stress the test structure, various techniques are used, where the most effective are thermal and surface vacuum techniques. The thermal shearography is used to inspect near skin-to-core bondline, ramp areas and solid graphite laminates, whereas, vacuum stress shearography is used to examine both near and far side bond lines in the honeycomb areas. Thermal stress shearography has been shown to be capable of inspecting large areas of composite and honeycomb materials at a rate of 60-ft.^{2}/hour. Example of testing the Payload Bay Doors (PLBD) removed from the Discovery Space Shuttle OV-103 using thermal stress shearography is shown in Figures 23a and 23b [Davis, 1996]. Disbond indications as small as 2.0x0.75-cm were imaged along the honeycomb ramp area.



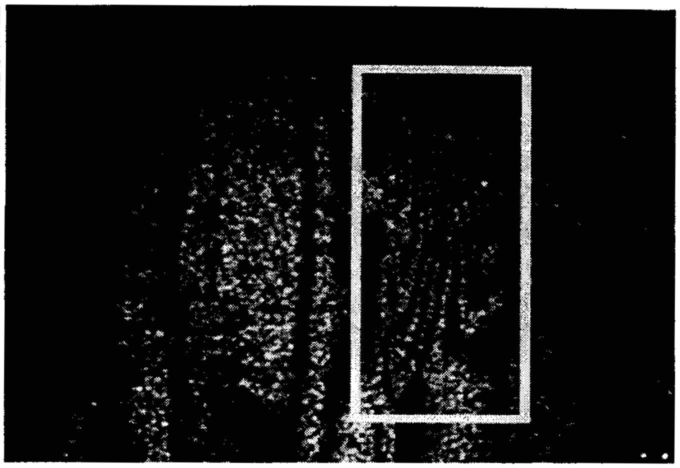


Figure 23a: Tripod mounted shearography camera/laser is shown inspecting the aft end of PLBD at location of delamination in a solid laminate frame member.

Figure 23b: A shearographic view of a 16.5x6-cm delamination indication (highlighted in the white frame).

THERMOGRAPHY

The effect of flaws on the thermal conductivity and emissivity of test materials is analyzed by the thermographic NDE method [Jones & Berger, 1992]. Its attractive features are the capability to cover large areas in a single frame and it does not require coupling. Unfortunately, this method was found unreliable when testing bonded joints with a narrow gap between the unbonded surfaces. In the early stages, liquid crystals were used to map the surface distribution of the temperature. The improvement of infrared systems made such tools highly sensitive and effective for mapping the cooling or heating profiles to rapidly indicate flaws. Examining the temporal gradient of the thermal maps, i.e., thermal flux, significantly improved the detectability of flaws.

Thermal Wave Imaging

Thermal waves transmitted through test parts can be received and used to produce an image of the internal uniformity. In addition to imaging the pattern of subsurface flaws and corrosion, the technique can rapidly (a few seconds) make quantitative measurements of less than 1% material loss for various regions in the image [Favro & Thomas, 1995 and Hans, et al, 1996]. It can use as a heat source pulses from photographic flash-lamps. The heat source box traps and funnels the light uniformly onto the test structure, and an infrared (IR) focal plane array camera, aimed and focused at the surface through an opening in the rear of the hand-held shroud, monitors the rapid cooling of the surface. The system operates by sending a heat pulse from the surface into the material, where it undergoes thermal wave reflection at either the rear surface or at any interior surface at which the thermal impedance changes, e.g., at disbonds, delaminations, etc. The effect of these thermal wave reflections is to modify the local cooling rate of the surface. The cooling rate, in turn, is monitored through its effect on the IR radiation from the surface, which is detected by the camera, and processed as a sequence of images by the control computer. The contrast in the processed images reveals the presence of defects in the interior or variations in the thickness of the material. In Figure 24, Thermal Wave Image an example is shown for corrosion and unbond near a tear strap/stringer of a Boeing 737

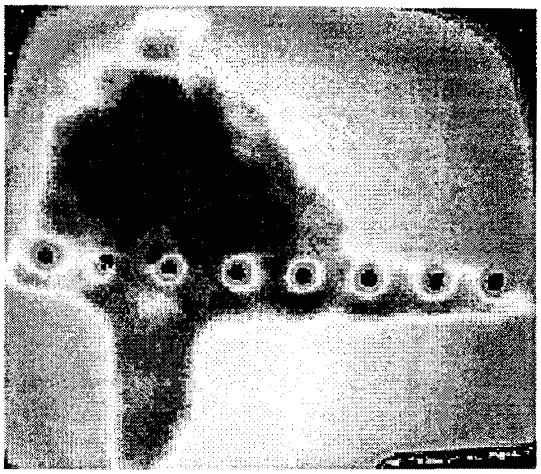


Figure 24: Thermal Wave Image of Corrosion and Disbonding near tear strap/stringer of a Boeing 737 [http://thermal.physics.wayne.edu/~han/han.html].

NDE ISSUES AND CHALLENGES

The continuing need for improved NDE methods resulted from the fact that each of the methods has certain capabilities and limitations with regards to detecting flaws and/or determining material properties. The selected method(s) and inspection requirements depend on the inspected material structural configuration and the life cycle stage. While in-service inspection of metallic structures require mostly the detection of fatigue cracks and corrosion, composites structures require the detection of delaminations and impact damage. Generally, unless a crack is located in a stack of plates beyond the second layer, many alternatives are available for its detection. Cracks need to be detected above a critical size and determine its size and depth. In contrast to this relatively simple requirement, corrosion detection and characterization and NDE of composite structures are more complex.

Metallic Structures in service

In service, two major types of flaws are commonly sought to be detected: fatigue cracks and corrosion. Generally, fatigue cracks are initiated at high cyclic stress areas and therefore it is relatively easy to determine when and where to expect them and their geometry is relatively simple. On the other hand, the issue of corrosion damage is much more complicate -- it is not defined by a single discontinuity type and it cannot be described by simple geometrical configuration. The damage is a relatively slow material degradation process [Hagemaier, Wendelbo & Bar-Cohen, 1985]. It is a general term that describes the oxidative degradation of metals caused by a local galvanic cell between the base metal (acting as anodic sites), at sites of defective protective coating, having the passive sites sustaining cathodic reaction. The corrosion process converts the metal into its oxide or hydroxide forms resulting in deterioration of its mechanical properties. Corrosion in aluminum alloys and plated steel surfaces can often be recognized by dulling or pitting of the area, and sometimes by white or red powdery deposits. It may also be the origin of, or revealed by, delamination, cracking, metal thinning, fretting, etc.

Corrosion can appear in many forms, depending on the type of metal, how it is processed, its surrounding structure and service conditions. Corrosion results from exposure to humid or corrosive environments and involves primarily electrochemical action at chemical/metallurgical/physical heterogeneity, with dissimilar potentials. In Table 1, a list of corrosion types that may appear in aircraft metallic components, their sources of formation and by-products, is given.

Aircraft are designed and manufactured with built-in corrosion-prevention features. However, most metals used in aircraft structures are subjected to degradation due to exposure to adverse environments including humidity-induced stresses and wide temperature excursions. These conditions may cause localized corrosion attacks in various forms. Corrosion-protection systems are widely in use and they consist of a combination of materials, sealants, paints, design details, drainage, assembly practice, and preventive maintenance. The corrosion-prevention system cannot be guaranteed to work. The severity of corrosion attacks varies with aircraft type, design techniques, operating environments, and operators' maintenance programs. Common areas of corrosion problems are listed below:

- floor and structure in the vicinity of lavatory systems and galleys,
- structures surrounding doors, particularly landing gear doors,
- wing skin adjacent to countersunk fastener heads,
- aluminum-faced honeycomb panels used for exterior panels and floors,
- wing-to-body joint fittings,
- fuselage lower structure (bilge area),
- areas having environmentally unstable materials, and
- structures susceptible to protective treatment damage during installation and repair, abrasion, fretting, and erosion.

In spite of careful maintenance programs to assure a lower rate of progress of corrosion damage (proper sealing or cleaning in galley area, proper draining, etc.), corrosion does occur and effective NDE techniques are needed to detect them as early as possible. Detection of each of the corrosion types described in Table 1 may require a different NDE approach due to the unique characteristics that are involved. Recent efforts are directed to avoiding removal of the paint or coating prior to inspection in order to minimize the associated environmental impact as well as cost. Several NDE methods are widely used for corrosion detection and evaluation. When the inspected area is physically accessible, visual tests are commonly used for periodic checks in search for cracks, change of color, change of texture, or bulges. Sometimes, tools such as magnifying glasses or boroscopes are employed for further evaluation or for less accessible areas, respectively. Surface corrosion at its embryonic stage can be visually detected from localized indication such as discoloration, faint powder lines, pimples on the paint and paint damage. Concealed corrosion is very difficult to detect since in most cases the characteristics of the damage are not sufficient to trigger an indication in conventional NDE tests. Generally, several NDE methods are available to detect and characterize hidden corrosion including X-ray and neutron radiography, ultrasonics, eddy current, and acoustic emission. All existing NDE methods for detection of corrosion are limited in capability and sensitivity. Frequently, corrosion is detected only after several subsequent inspection schedules, in which case the damage is fairly extensive and may require the replacement of the structural component involved.

TABLE 1: Corrosion types, which can inflict damage to aircraft strictures, and their characteristics.

Corrosion type	Source	Appearance	By-Product	Notes
Crevice	Afflicts mechanical joints, e.g., coupled pipes or threaded connections. Triggered by local environment composition differences (O_2 concentration).	Localized damage in the form of scale and pitting.	Same as scale and pitting.	• Caused by differential aeration. • Difference in oxygen concentration produces potential difference and leads to flow of electrical currents across aerated (cathode) and derated (anode) portions of the metal. • Causes localized corrosion failure.
Filiform	High humidity around fasteners, skin joints or breaks in coating cause an electrolytic process.	Meandering, fine, thread-like trenches spreading from the source.	Similar to scale.	
Galvanic Corrosion	Corrosive condition that results from contact of different metals.	Uniform damage, scale, surface fogging or tarnishing.	Emission of mostly molecular hydrogen gas in a diffused form.	• Slow growth rate. Expressed as penetration/year or weight loss per unit-area/day, e.g. the rate for aluminum in open atmospheric conditions of Los Angeles, CA is 0.02-mil/yr. • For Ti and Al alloys the rate is slow and therefore it does not pose serious structural problems. • The metal with the most negative potential suffers the most damage.
Inter-granular	Presence of strong potential differences in grain or phase boundaries.	Appears at the grain or phases boundaries as uniform damage.	Produces scale type indications at smaller magnitude than stress corrosion.	• The severity and rate of growth depends on the material microstructure crystalinity and segregation. • This type of corrosion can merely result increased susceptibility to attack in the form of pitting or stress cracking. • Exfoliation occurs in layered grains (e.g. rolled sheets) in the form of laterally extended damage. • Aluminum is susceptible to such attack mainly in an environment of chlorine ions and dissolved oxygen.
Microbial	Bacterial, fungus or yeast in contaminated kerosene-type jet engine fuel.	Appears in integral fuel tanks.	Combination of by-product of pitting and scale.	Can be eliminated by a proper maintenance of the fuel in the tank.
Pitting	Impurity or chemical discontinuity in the paint or protective coating.	Localized pits or holes with cylindrical shape and hemispherical bottom.	Rapid dissolution of the base metal.	• Expressed in terms of pitting depth (i.e. pitting factor). • Pitting can be critical to the structural integrity. • Can be detected by AC impedance or electrochemical impedance spectra analysis.

				• Usually pitting is accompanied by an order of magnitude change in the local resistance and capacitance.
Stress Corrosion Cracking	Mechanical tensile stresses combined with chemical susceptibility.	Localized micro-macro-cracks at shielded or concealed areas.	Produces initially scale type indications at a large magnitude that progresses to cracking.	• Causes critical failure of structures. • Failure rate is determined by the stress levels. • Corrosion fatigue occurs under cyclic stresses. • Stress and rubbing action remove protection and lead to fretting corrosion as a result of contact of the metal surface with particles introduced by the abrasion process.
Thermo-galvanic Corrosion	Caused by thermal gradients parallel to the metal surface.	Localized attack correlated with temperature distribution.	Produces scale indications.	Hot portion of the metal serves as cathode whereas the cold portion as anode.

NDE of Composite Materials

The high stiffness to weight ratio, low electromagnetic reflectance and the ability to embed sensors and actuators have made fiber-reinforced composites an attractive construction material for primary aircraft structures. These materials consist of fibers and a polymer matrix that are stacked in layers and then cured. A limiting factor in widespread use of composites is their high cost - composite parts are about at least an order of magnitude more expensive than metallic parts. The cost of inspection is about 30% of the total cost of acquiring and operating composite structures. This large portion of the total cost makes the need for effective inspection critical not only to operational safety but also to the cost benefit of these materials [Bar-Cohen, 1986, and Bar-Cohen, et al, 1991]. Currently, there are several critical issues that are still challenging the NDE community with regards to inspection of composites. These issues include:

- <u>**Defect Detection and Characterization**</u>: Composites are susceptible to the formation of many possible defects throughout their life cycle mostly due to the multiple step production process, their non-homogeneity and the brittle matrix. These defects include delaminations, cracking, fiber fracture, fiber pullout, matrix cracking, inclusions, voids, and impact-damage. Table 2 lists some of the defects that may appear in composite laminates and their effect on structural performance. While the overall inspection emphasis is on detection of delaminations, porosity and impact damage, Table 2 is showing that other defects can have a critical effect on the performance of the host structures. Therefore, it is essential to be able to characterize the hosted flaws in order to estimate their effect on the structural integrity.
- <u>**Material Properties Characterization**</u>: Production and service conditions can lead to property degradation and sub-standard performance of primary structures. Causes for such degradation can be the use of wrong constituent (fiber or matrix), excessive content of one of the constituent (resin rich or starved), wrong stacking order, high porosity content, micro-cracking, poor fiber/resin interface aging, fire damage, and excessive environmental/ chemical/radiation exposure. Current destructive test methods of determining the elastic properties are using representative coupons. These methods are costly and they are not providing direct information about the properties of represented structure.

- **Need for Rapid Large Area Inspection**: Impact damage can have critical effect on the structure capability to operate in service (see Table 2). This critical type of flaw can be induced during service life anywhere on the structure and it requires detection as soon as possible rather than waiting for the next scheduled maintenance phase. Repeated application of conventional NDE for verification of the structural integrity can be very expensive and takes aircraft out of their main mission. Since impact damage can appear anywhere, there is a need for a low-cost system that can be used to rapidly inspect large areas in field condition.
- **Real-Time Health Monitoring**: A system of health-monitoring is needed to reduce the periodic inspection, which requires the temporary removal of the aircraft from service. Fundamentally, such health monitoring systems emulate biological systems, where onboard sensors track the structural integrity throughout the life cycle. The life cycle starts from production and continues through service and it is essential to have an alarm to indicate that a critical parameter was exceeded.
- **Smart Structures**: The availability of compact actuators, sensors and artificial intelligence has made it possible to develop structures that self-monitor their own integrity and use actuators to avoid or timely respond to threats. The changing environment or conditions can be counteracted by adequate combination of actuators and sensors that change the conditions and/or dampen the threat. Artificial intelligence can be used to assure the application of the most effective response at the shortest time. An example of the application of smart structures is the reduction of vibrations that lead to fatigue.
- **Residual Stresses**: Current state of the art does not provide effective means of nondestructive determination of residual stresses. Technology is needed to detect and relieve residual stresses in structures made of composite materials.
- **Weathering and Corrosion Damage**: Composites that are bonded to metals are sensitive to exposure to service fluids, hygrothermal condition at elevated temperatures and to corrosion. Particular concern rises when aluminum or steel alloys are in a direct contact with graphite/epoxy or with graphite/polyimide laminates. The graphite is cathodic to aluminum and steel and therefore the metal, which is either fastened or bonded to it, is eroded. In the case of graphite/epoxy, the metal deteriorates, whereas in the case of graphite/polyimide defects are induced in the composite in the form of microcracking, resin removal, fiber/matrix interface decoupling and blister (e.g. delaminations). When an aluminum panel is coupled to a Gr/Ep protective coating the aluminum is subjected to a significant loss of strength. To prevent such degradation, a barrier layer is needed between the metal and the graphite/epoxy, where many times glass/epoxy or Kevlar/epoxy layers are used.

For many years, the multi-layered anisotropic nature of composites posed a challenge to the NDE research community. Pulse-echo and through-transmission are still the leading standard NDE methods of determining the quality of composites. However, these methods provide limited and mostly qualitative information about defects and material properties. The discovery of the Polar Backscattering [Bar-Cohen & Crane, 1982] and the leaky Lamb wave (LLW) [Bar-Cohen & Chimenti, 1984] phenomena in composites enabled effective quantitative NDE of composites.

TABLE 2: Effect of defects in composite materials

Defect	Effect on the material performance
Delamination	Catastrophic failure due to loss of interlaminar shear carrying capability. Typical acceptance criteria require the detection of delaminations that are $\geq$0.64-cm.

Impact damage	The effect on the compression static strength • Easily visible damage can cause 80% loss • Barely visible damage can cause 65% loss
Ply gap	Degradation depends on stacking order and location. For $[0,45,90,-45]_{2S}$ laminate: • 9% strength reduction due to gap(s) in 0° ply • 17% reduction due to gap(s) in 90° ply
Ply waviness	• Strength loss can be predicted by assuming loss of load-carrying capability. • For 0° ply waviness in $[0,45,90,-45]_{2S}$ laminate, static strength reduction is: - 10% for slight waviness - 25% for extreme waviness • Fatigue life is reduced at least by a factor of 10
Porosity	• Degrades matrix dominated properties • 1% porosity reduces strength by 5% and fatigue life by 50% • Increases equilibrium moisture level • Aggravates thermal-spike phenomena
Surface notches	• Static strength reduction of up to 50% • Local delamination at notch • Strength reduction is small for notch sizes that are expected in service
Thermal Over-exposure	Matrix cracking, delamination, fiber debonding and permanent reduction in glass transition temperature

CONCLUSIONS

As the 2nd Millennium is coming to an end, it is interesting to look back and see how far the field of NDE has been advanced so far and what are still the challenges. Like many other fields, improvements were made in every aspect of the NDE science and engineering where computers and internet contributed greatly to the rapid advancement. The various NDE methods were benefited with better inspection techniques. Also, efforts are increasingly being made to integrate several methods to form multi-mode systems that take advantage of the complementary capabilities to increase the functionality as well as the overlapping capabilities to improve the reliability.

Some technologies affected most or all the NDE methods and those include the use of computer graphics and interactive simulation to investigate the response of the specific methods. The effect of flaws on the wave response is analyzed using theoretical models and analytical tools, including finite element techniques. Also, inversion techniques are developed to extract flaw characteristics and material properties using nondestructive measurements.

Sensors can be divided into the following groups

- Remote sensors - Eddy current, magnetic, visual, dry-couple ultrasonics, etc.
- Attached sensors - Cracking fuse, resistance gauging, strain gage, acoustic emission, ultrasonic, eddy current, fiber optics
- Sensitive coating - Bruising paint indicator, brittle coating, liquid crystals
- Imbedded sensors - Fiber optics, dielectric, eddy current, magnetic, ultrasonics

The most practical sensors currently used are the ones that either operated remotely or attached to the test structures. The manufacturers and user are still not receptive to using sensors that are imbedded or permanently attached or coated. This is due to the addition in weight and the potential effect on the structural integrity. The use of stick-on wireless type sensors are expected to emerge in the coming years allowing to monitor structural integrity throughout structures life cycles without disassembly, redesign or complex wiring.

The use of the crawler technology, which was enabled by JPL, is offering great potential to rapid field inspection, where plug-and-ply boards would define the crawler functionality. Employing off-the-shelf components and standard personal computers bus structure (e.g., ISA, PCI etc.) can lead to a significant reduction in system cost. Currently, NDE hardware manufacturers have to develop a complete instrument each time a new product is introduced. It is envisioned that concentration on the development of components with focused NDE functionality (e.g., ultrasonics) will have great payoff. It would lead to substantially greater affordability of future instruments and to a faster transition of NDE technology to commercial use. Since the 96 ASNT Fall Conference, the author started holding Sessions on the topic of Robotics and Miniaturized NDT Instruments. The intent of these Sessions is to attract industry and academia attention to the topic of developing generic mother-crawler and related plug-in modules. Recent government interest in addressing the issue of NDE of corrosion turned the spotlight onto MACS as a potential baseline for robotic multi-sensor platform for rapid scanning of aircraft structures. In future generations of this technology, micro-electronic mechanical systems (MEMS) is expected to lead to extremely small NDE instruments and scanners. Insect-size micro-scanners may potentially crawl into an aircraft engine and other hidden areas and perform inspection or other maintenance tasks.

Advancement in miniature electronics, actuators, robotics, wireless communication as well as sensors are expected to make great impact on the field of NDE in the coming years. The search for smarter methods that can rapidly and inexpensively detect very small flaws in complex materials and structures at very high probability and repeatability will continue to be a challenge for NDE. Efforts will be made to further reduce the complexity associated with inspection procedures, where redundant tasks will be performed by computers leaving the role of the human operator to critical decision making. While it is difficult to predict when, global standards will eventually be accepted worldwide and will cover all the NDE standards, inspection procedures and personnel training/qualifications.

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